





# What drives the evolution of gas kinematics in star-forming galaxies?

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## ABSTRACT

One important result from recent large integral field spectrograph (IFS) surveys is that the intrinsic velocity dispersion of galaxies traced by star-forming gas increases with redshift. Massive, rotation-dominated discs are already in place at  $z \sim 2$ , but they are dynamically hotter than spiral galaxies in the local Universe. Although several plausible mechanisms for this elevated velocity dispersion (e.g. star formation feedback, elevated gas supply, or more frequent galaxy interactions) have been proposed, the fundamental driver of the velocity dispersion enhancement at high redshift remains unclear. We investigate the origin of this kinematic evolution using a suite of cosmological simulations from the FIRE (Feedback In Realistic Environments) project. Although IFS surveys generally cover a wider range of stellar masses than in these simulations, the simulated galaxies show trends between intrinsic velocity dispersion ( $\sigma_{\text{intr}}$ ), SFR, and  $z$  in agreement with observations. In both observations and simulations, galaxies on the star-forming main sequence have median  $\sigma_{\text{intr}}$  values that increase from  $z \sim 0$  to  $z \sim 1$ –1.5, but this increasing trend is less evident at higher redshift. In the FIRE simulations,  $\sigma_{\text{intr}}$  can vary significantly on time-scales of  $\lesssim 100$  Myr. These variations closely mirror the time evolution of the SFR and gas inflow rate ( $\dot{M}_{\text{gas}}$ ). By cross-correlating pairs of  $\sigma_{\text{intr}}$ ,  $\dot{M}_{\text{gas}}$ , and SFR, we show that increased gas inflow leads to subsequent enhanced star formation, and enhancements in  $\sigma_{\text{intr}}$  tend to temporally coincide with increases in  $\dot{M}_{\text{gas}}$  and SFR.

**Key words:** galaxies: evolution – galaxies: kinematics and dynamics – galaxies: structure.

## 1 INTRODUCTION

The increasing capabilities of optical and near-infrared integral field spectrographs (IFSs) have revealed the internal dynamics of hundreds of star-forming galaxies out to  $z \lesssim 3$  (see the review by Glazebrook 2013). The majority of IFS surveys at  $z > 1$  probe the kinematics of ionized gas using tracers such as  $H\alpha$ , [OIII], and [OII]. Whereas the spatially resolved kinematics traced by stars

and other phases of gas have been routinely measured for nearby galaxies (e.g. de Zeeuw et al. 2002; Helfer et al. 2003; Walter et al. 2008; Falcón-Barroso et al. 2017), at  $z > 1$ , such measurements are either currently unattainable (stars and atomic gas) or only limited to a small number of galaxies (molecular gas; e.g. Hodge et al. 2012). The IFS surveys at  $1 \lesssim z \lesssim 3$  reveal that a significant fraction ( $> 1/3$ ) of massive galaxies ( $M_* \gtrsim 10^{10} M_{\odot}$ ) exhibit smooth velocity gradients, indicative of rotating discs, whereas the rest exhibit irregular, merger-like kinematics or are dispersion-dominated (e.g. Flores et al. 2006; Förster Schreiber et al. 2009; Law et al. 2009; Lemoine-Busserolle et al. 2010; Gnerucci et al. 2011; Epinat

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et al. 2012; Wisnioski et al. 2015; Mieda et al. 2016; Stott et al. 2016; Mason et al. 2017). Although the exact statistical breakdown depends on the sample selection, the spatial and spectral resolutions of the IFS observations, and the adopted galaxy classification schemes (e.g. Hung et al. 2015; Bellocchi, Arribas & Colina 2016; Rodrigues et al. 2016), these results all point to an early emergence of massive, rotating disc-like galaxies at  $z \gtrsim 1$ .

A key difference between these massive rotating discs at  $z \gtrsim 1$  and spiral galaxies in the local Universe is that the intrinsic velocity dispersions traced by ionized gas (hereafter  $\sigma_{\text{intr}}$ ) of  $z \gtrsim 1$  systems are significantly higher than those of their local counterparts (see Yuan et al. 2017, for a rare exception). These high- $z$  disc-like galaxies typically have  $\sigma_{\text{intr}}$  of 50–100 km s<sup>−1</sup> and rotation velocity-to-dispersion ratios ( $V/\sigma_{\text{intr}}$ ) of 1–5 (Förster Schreiber et al. 2009; Law et al. 2009; Jones et al. 2010; Genzel et al. 2011), although it is worth noting that the scatter within individual surveys is large and the measurements of  $\sigma_{\text{intr}}$  and beam-smearing corrections differ amongst surveys. Nearby spiral galaxies tend to have a factor of 2–5 lower  $\sigma_{\text{intr}}$  (e.g. Epinat et al. 2010; Zhou et al. 2017). This trend of decreasing  $\sigma_{\text{intr}}$  with decreasing  $z$  is also seen in slit-based observations (e.g. Kassin et al. 2012; Simons et al. 2016). In the local Universe, only more extreme systems – such as ultraluminous and luminous infrared galaxies (ULIRGs and LIRGs), Lyman break galaxy (LBG) analogues, and H $\alpha$  emitters – exhibit  $\sigma_{\text{intr}}$  values comparable to those of high- $z$  systems (Gonçalves et al. 2010; Bellocchi et al. 2013; Green et al. 2014).

The elevated  $\sigma_{\text{intr}}$  in high- $z$  galaxies has been associated with enhanced turbulent motions. However, the physical driver(s) of the enhanced turbulence (e.g. feedback or gravitational instability) remains unclear. Lehnert et al. (2009, 2013) show that there is a positive correlation between  $\sigma_{\text{intr}}$  and star formation rate (SFR) surface density at  $z \sim 2$  (although see also Genzel et al. 2011), possibly suggesting that the enhanced  $\sigma_{\text{intr}}$  is driven by star formation feedback processes such as supernovae and radiation pressure (e.g. Thompson, Quataert & Murray 2005; Dib, Bell & Burkert 2006; Ostriker & Shetty 2011; Shetty & Ostriker 2012; Faucher-Giguère, Quataert & Hopkins 2013; Martizzi, Faucher-Giguère & Quataert 2015; Hayward & Hopkins 2017; Orr et al. 2017). Direct kinematic evidence for shells, bubbles, and outflows in M33 may also support such models (Kam et al. 2015). Further evidence for a positive correlation between  $\sigma_{\text{intr}}$  and integrated SFR across a large redshift range is compiled in Green et al. (2014).

It has also been claimed that gravitational instabilities due to external sources, such as cosmological gas accretion and galaxy interactions (e.g. Dekel, Sari & Ceverino 2009; Bournaud et al. 2011), or internal dynamics, such as disc instabilities and clump-clump interactions (e.g. Wada, Meurer & Norman 2002; Agertz et al. 2009; Dekel et al. 2009; Ceverino, Dekel & Bournaud 2010), are responsible for the elevated  $\sigma_{\text{intr}}$  exhibited by high- $z$  galaxies. Several studies have found that the evolution of gas fraction (in a marginally stable disc) can explain the increase in  $\sigma_{\text{intr}}$  with  $z$  (e.g. Swinbank et al. 2012b; Wisnioski et al. 2015; Turner et al. 2017). Recent work by Krumholz & Burkhardt (2016) argues that the correlation between  $\sigma_{\text{intr}}$  and SFR is more consistent with gravitational instability-driven turbulence rather than stellar feedback-driven turbulence when galaxy gas fractions are taken into account, and this gravitational instability-driven turbulence is stronger in starbursts and high- $z$  galaxies than quiescently star-forming galaxies (Krumholz et al. 2018). However, this analytic work is yet to be tested with detailed simulations.

A number of observational effects can complicate the measurement of  $\sigma_{\text{intr}}$  and its physical interpretation. It is increasingly difficult

at higher redshift to probe the detailed kinematics of galaxies and make a fair comparison with their local counterparts due to surface brightness dimming and limited spatial resolution. Based on a set of artificially redshifted local spiral galaxies, Epinat et al. (2010) conclude that the mean kinematic properties can be recovered with proper disc modelling and beam-smearing corrections. However, this conclusion may not hold when galaxies exhibit more complicated intrinsic kinematic structures (e.g. Gonçalves et al. 2010). Furthermore, to reduce a two-dimensional velocity dispersion map to a single value of  $\sigma_{\text{intr}}$ , some studies incorporate an isotropic velocity dispersion in the disc model and find a best-fitting  $\sigma_{\text{intr}}$  (e.g. Cresci et al. 2009), whereas some studies simply employ a flux-weighted mean (e.g. Law et al. 2009). Some authors apply corrections for beam smearing (e.g. Stott et al. 2016), whereas some studies do not; simulations suggest that the effects of beam smearing can be significant even for high-resolution H $\alpha$  kinematic maps of nearby galaxies (Pineda et al. 2017).

In this study, we aim to explore the physical drivers of  $\sigma_{\text{intr}}$  in star-forming galaxies using a suite of cosmological simulations from the FIRE project<sup>1</sup> (Feedback In Realistic Environments; Hopkins et al. 2014). In parallel, we gather measurements of  $\sigma_{\text{intr}}$  of star-forming galaxies at  $0 \leq z \lesssim 3$  from IFS surveys presented in the literature. We describe the simulation suite and the derivation of physical and kinematic properties in Section 2. In Section 3, we compile a set of IFS observations from the literature and compare their physical and kinematic properties with the simulated galaxies. We discuss possible physical drivers of the enhanced velocity dispersion of high- $z$  galaxies in Section 4. Finally, we discuss the implications of our results in Section 5 and list our conclusions in Section 6.

## 2 SIMULATIONS AND ANALYSES

### 2.1 FIRE simulations

The simulations in this paper were run as part of the FIRE project; specifically, the original ‘FIRE-1’ version of the code from Hopkins et al. (2014) was used.<sup>2</sup> They were run using the pressure-energy smoothed-particle hydrodynamics (‘P-SPH’) mode of GIZMO<sup>3</sup> (Hopkins 2015), a multimethod gravity plus hydrodynamics code. This formulation of SPH improves the treatment of fluid mixing instabilities and includes various other improvements to the artificial viscosity, artificial conductivity, higher order kernels, and time-stepping algorithm designed to reduce the most significant known discrepancies between SPH and grid methods (Springel 2010; Hopkins 2013; Hayward et al. 2014a). The gravity solver is an improved version of the Tree-PM solver from GADGET-3 (Springel 2005), with fully adaptive (and fully conservative) gravitational force softening for gas following Price & Monaghan (2007).

<sup>1</sup><http://fire.northwestern.edu>

<sup>2</sup>We note that after the bulk of the analysis in this paper was performed, some of the haloes analysed in this work were re-simulated using the ‘FIRE-2’ version of GIZMO (Hopkins et al. 2017), which employs an improved numerical method (the meshless finite mass scheme presented in Hopkins 2015) and an improved algorithm for coupling momentum and energy from stellar feedback to the ISM (Hopkins et al. 2018). To maintain consistency (not all of the haloes included here have been re-simulated with the FIRE-2 code) and avoid redoing our analysis, we have opted to analyse the FIRE-1 simulations. However, we repeated our analysis for one of the FIRE-2 simulations (m12i) and found that our conclusions are robust.

<sup>3</sup><http://www.tapir.caltech.edu/~phopkins/Site/GIZMO.html>

The physics, source code, and all numerical parameters are described in detail in the papers above, but for completeness, we briefly review them here. Radiative heating and cooling are treated (via CLOUDY tabulations; Ferland et al. 1998) from 10 to  $10^{10}$  K, including atomic, molecular, and metal-line cooling processes (following 11 species independently) and accounting for photoheating both by a UV background (Faucher-Giguère et al. 2009) and local sources, in addition to self-shielding. Stars are spawned stochastically from gas that meets the following criteria: (1) it is self-gravitating according to the Hopkins, Narayanan & Murray (2013b) criterion, (2) it is molecular and self-shielding (following Krumholz & Gnedin 2011), and (3) its density is greater than a minimum density threshold  $n_{\min} \sim 5\text{--}50\text{ cm}^{-3}$ , depending on the mass resolution – and thus maximum density resolved – of a given simulation. The instantaneous SFR density is determined by dividing the molecular gas density by the local free-fall time (i.e. an instantaneous star formation efficiency of 100 per cent in the absence of feedback is assumed). However, stellar feedback disrupts clouds on time-scales shorter than the local free-fall time, so the resulting star formation efficiency is less than 100 per cent except for at very high gas surface density (Faucher-Giguère et al. 2013; Orr et al. 2017; Grudić et al. 2018).

Once a star particle is formed, the simulations explicitly incorporate the following stellar feedback mechanisms: (1) local and long-range momentum flux from radiation pressure (both in the initial UV/optical single-scattering regime and re-radiated light in the IR); (2) energy, momentum, mass, and metal injection from supernovae (Types Ia and II) and stellar mass-loss (both OB and AGB stars); and (3) photoionization and photoelectric heating. Every star particle is treated as a single-age stellar population with known mass, age, and metallicity. Given this information, all feedback event rates, luminosities, energies, mass-loss rates, and all other relevant quantities are tabulated directly from STARBURST99 (Leitherer et al. 1999) stellar evolution models, assuming a Kroupa (2001) IMF. Note that AGN accretion and feedback are not implemented in these simulations.

The specific sample of simulations studied in this paper includes simulations that were first presented in Hopkins et al. (2014) and Faucher-Giguère et al. (2015). Specifically, we focus on three simulations (m12v, m12q, and m12i) from Hopkins et al. (2014), for which the  $z = 0$  halo masses are in the range  $\sim(0.6\text{--}1.2) \times 10^{12} M_{\odot}$ , and the central galaxies have  $z = 0$  stellar masses of  $\sim(2.2\text{--}6.1) \times 10^{10} M_{\odot}$ . These haloes experience widely different accretion and merger histories: m12v, which uses higher resolution initial conditions from Kereš & Hernquist (2009), has a violent merger history with several encounters at  $z < 2$ . The m12q and m12i haloes, which were drawn from the AGORA project (Kim et al. 2014), have less violent histories than m12v. Since the  $z = 2$  stellar mass values of the aforementioned simulations are about an order of magnitude lower than those of typical galaxies observed in high- $z$  IFS surveys (with the exception of lensed galaxies), we also analyse an additional seven simulations of more massive haloes from Faucher-Giguère et al. (2015), which were only run to  $z = 2$  (the ‘z2h’ series). The z2h simulations are representative of more-massive haloes at  $z = 2$ : they have  $z = 2$  stellar masses of  $(0.3\text{--}4) \times 10^{10} M_{\odot}$  and  $z = 2$  halo mass of  $(0.2\text{--}1.2) \times 10^{12} M_{\odot}$ .

Whereas earlier studies have explored the role of accretion in driving turbulence via numerical experiments with idealized discs (e.g. Hopkins, Kereš & Murray 2013a) or analytic models (e.g. Elmegreen & Burkert 2010; Genel, Dekel & Cacciato 2012), cosmological simulations are superior for studying this process because accretion of primordial gas at early times and recycled gas at later

times is treated self-consistently and depends on, e.g. environment in a manner that cannot be easily treated via idealized simulations and analytic models but is incorporated naturally in cosmological simulations. Furthermore, these high-resolution simulations (with minimum baryonic force softening lengths of  $\lesssim 10$  pc) enable accurate treatments of stellar feedback processes, as summarized above, and thus allow us to study the effect of stellar feedback on the velocity dispersions of galactic gaseous discs.

## 2.2 Physical properties of the FIRE galaxies

We trace the evolution of the most massive halo in each simulation from  $z = 4$  to 0 for the m12v, m12q, and m12i simulations and from  $z = 4$  to 2 for the z2h simulations. Using halo catalogues and merger trees generated by running Amiga’s Halo Finder (Knollmann & Knebe 2009), we determine the properties of the main halo and the central galaxy that it hosts at each snapshot time. We derive the kinematic properties of the simulated galaxies based on the dynamical information traced by the star-forming gas (i.e. SPH particles with  $\text{SFR} > 0$ ); this is motivated by the goal to compare with recent IFS surveys that use nebular lines (e.g.  $\text{H}\alpha$ ,  $[\text{O III}]$ , and  $[\text{O II}]$ ) as kinematic tracers. Following Hung et al. (2016), we construct projected velocity and velocity dispersion maps along a given line of sight by measuring the SFR-weighted median and standard deviation within  $500\text{ pc} \times 500\text{ pc}$  pixels. Fig. 1 shows example SFR surface density and kinematic maps of selected snapshots of the m12i simulation.

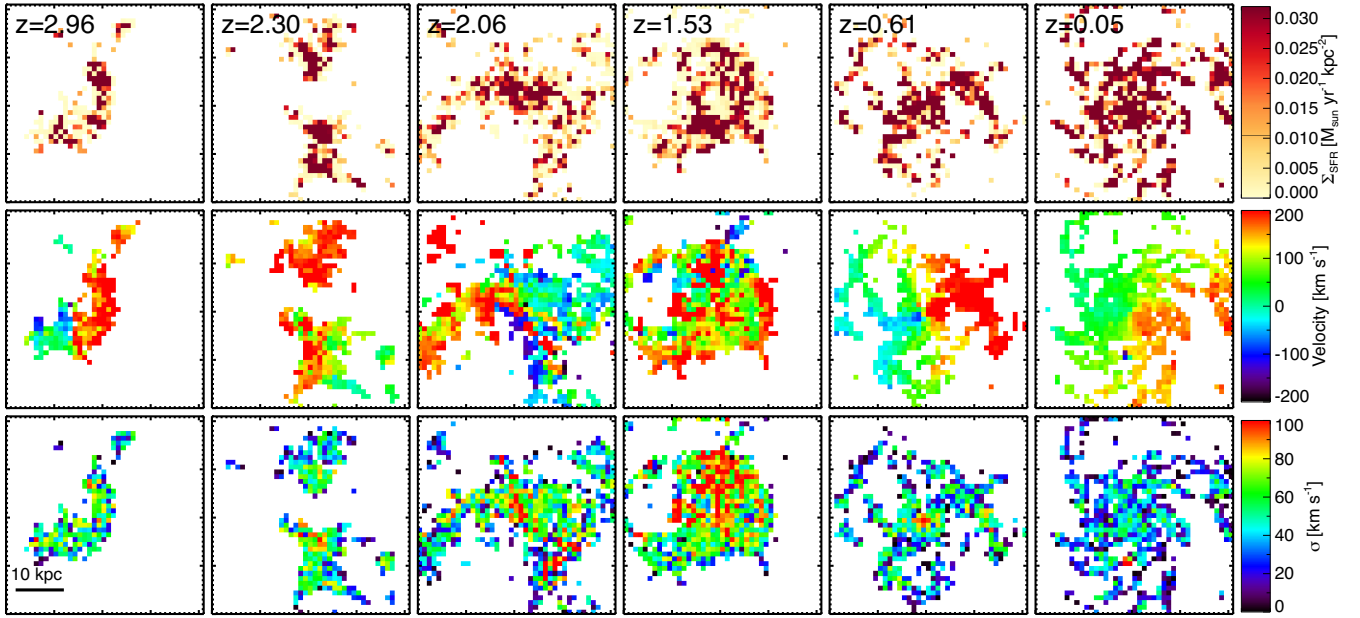
We measure a set of quantities that may be physical drivers of or are well correlated with galaxy kinematics, including the SFR (e.g. Lehnert et al. 2009; Green et al. 2010, 2014),  $M_*$  (e.g. Stott et al. 2016), and gas fraction (e.g. Wisnioski et al. 2015; Krumholz & Burkert 2016). The SFRs ( $M_*$  values) of the selected massive haloes are defined as the total SFR ( $M_*$ ) of gas (star) particles within  $0.2 R_{\text{vir}}$  of the halo centre.<sup>4</sup> For the comparison with observations presented in Section 3, we use the time-averaged SFR calculated based on young stars formed within 10 Myr at a given redshift. The gas fraction ( $f_{\text{gas}}$ ) is defined as the ratio of the gas mass to the sum of the gas and stellar masses within  $0.2 R_{\text{vir}}$ , where the gas mass is computed from the subset of gas particles with  $n \geq 1\text{ cm}^{-3}$ . SFR,  $M_*$ , and  $f_{\text{gas}}$  are insensitive to the chosen outer radius when a value of  $\gtrsim 0.1 R_{\text{vir}}$  is used. Although currently poorly constrained in observations, another quantity of interest is the gas inflow rate because gas inflow can lead to subsequent changes in the gas fraction (e.g. Tacconi et al. 2010) and/or contribute to the bulk and turbulent motion, especially in the case of a galaxy merger (e.g. Hung et al. 2016). Following Faucher-Giguère, Kereš & Ma (2011) and Muratov et al. (2015), we measure the gas inflow rate as the instantaneous mass flux through a thin spherical shell with an outer radius  $0.3 R_{\text{vir}}$  and inner radius  $0.2 R_{\text{vir}}$ :

$$\dot{M}_{\text{gas}} = \sum_i \mathbf{v}_i \cdot \frac{\mathbf{r}_i}{|r_i|} m_{\text{gas},i} / dL, \quad (1)$$

where  $dL = 0.1 R_{\text{vir}}$  and the infalling gas is defined as gas particles with  $\mathbf{v}_i \cdot \frac{\mathbf{r}_i}{|r_i|} < 0$ .

<sup>4</sup>The SFR is the ‘instantaneous’ SFR, which most closely corresponds to the  $\text{H}\alpha$  luminosity and other short-time-scale tracers [see e.g. Hayward et al. (2014b), Sparre et al. (2017), and Orr et al. 2017 for discussions] and will in general differ from longer time-scale tracers, such as the UV and FIR luminosities, for the simulated galaxies at  $z \gtrsim 1$ , where the star formation histories of even the relatively massive simulated galaxies considered here are very bursty (Sparre et al. 2017; Faucher-Giguère 2018).





**Figure 1.** Selected snapshots from the m12i simulation, with each column corresponding to a different redshift (indicated in the top-left corners of the top panels). The top row shows SFR density ( $M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ ) maps. The middle and bottom rows show velocity and velocity dispersion maps (in  $\text{km s}^{-1}$ ), respectively. Each panel is  $40 \text{ kpc} \times 40 \text{ kpc}$  in size. These maps are projected on to the  $x$ - $y$  plane (arbitrarily defined in the simulations) for all redshift snapshots.

### 2.3 Kinematic properties

We aim to define a proxy for intrinsic velocity dispersion that we can compare with the statistical trends from recent IFS observations and use to assess the overall kinematic evolution in individual cosmological simulations. We define a quantity  $\sigma_{1D}$  that is intended to be representative of deriving a flux-weighted mean with some corrections for the beam-smearing effect present in real observations. We calculate the SFR-weighted standard deviation of the velocity distribution within  $0.1 R_{\text{vir}}$  (typically  $\sim 10$ – $20 \text{ kpc}$ ) for  $10^4$  viewing angles for each galaxy and define  $\sigma_{1D}$  as the minimum value taken over the different viewing angles. The radius  $0.1 R_{\text{vir}}$  is chosen since it is comparable to the typical field of view of IFS observations. If we simply calculate a 1D velocity dispersion without minimizing over viewing angles, then this value would be unreasonably large, as it would also include significant large-scale motions, such as rotation (see Table 1). In cases in which clear disc-like kinematics are present,  $\sigma_{1D}$  represents the flux-weighted velocity dispersion measured along a face-on viewing angle. However, in cases with more complex kinematics, such as late-stage galaxy mergers (e.g. Bellocchi et al. 2013), the physical meaning of  $\sigma_{1D}$  is not as well defined and only broadly reflects the degree of disturbance of the kinematics.

We caution that  $\sigma_{1D}$  is not directly comparable to the values derived from IFS observations without performing radiation transfer of synthetic spectra, adding instrumental effects, and analysing the data cubes in the same manner as real observations. However, we have confirmed that  $\sigma_{1D}$  appears to be an unbiased tracer of the velocity dispersion derived from detailed kinematic modelling: for a subset of simulated galaxies exhibiting disc-like kinematics, we also derived the velocity dispersion based on modelling of the kinematic maps and data cubes in a manner more akin to observational work. We used the publicly available code <sup>3D</sup>Barolo (Di Teodoro & Fraternali 2015; Di Teodoro, Fraternali & Miller 2016) to fit tilted-ring models to the simulated galaxies in position–position–velocity

space. As shown in Fig. 2, the radially averaged velocity dispersion derived from the tilted-ring modelling agrees with the cruder  $\sigma_{1D}$  measure to within a factor of 2, and there is no obvious systematic bias.

## 3 A COMPARISON WITH OBSERVATIONS

### 3.1 Samples of simulated and observed galaxies

We compare the kinematic properties of the simulated galaxies from the FIRE project with observations from the literature. From all snapshots of the 10 simulations, we select the subset of central galaxies that are located on or above the star-forming galaxy main sequence (MS; Brinchmann et al. 2004; Noeske et al. 2007). The membership and the distance from the galaxy MS for each galaxy are determined based on the parametric form from Speagle et al. (2014), with a scatter of 0.2 dex. The distributions of  $M_*$ , SFR, and  $\sigma_{1D}$  are summarized in Table 1. We note that large-volume cosmological simulations find that the normalization of the galaxy MS in simulations is systematically lower than in observations at  $z \sim 2$  by up to  $\sim 0.5$  dex (e.g. Furlong et al. 2015; Sparre et al. 2015), and this may also be the case for the FIRE-1 simulations (Sparre et al. 2017), although the small number of haloes analysed in that work prevents a firm conclusion. For this reason, we have checked how sensitive our results are to the definition of the MS; we found that the differences in the median  $\sigma_{1D}$  derived here are typically less than  $10 \text{ km s}^{-1}$  when using different normalizations.

We compile the intrinsic velocity dispersion of star-forming galaxies at  $0 \lesssim z \lesssim 3$  from the literature: GHASP (Epinat et al. 2008, 2010), DYNAMO (Green et al. 2014), the LBA survey (Gonçalves et al. 2010), the MUSE/KMOS survey (Swinbank et al. 2017), KROSS (Stott et al. 2016; Harrison et al. 2017; Johnson et al. 2017), IROCKS (Mieda et al. 2016), MASSIV (Epinat et al. 2012; Queyrel et al. 2012), WiggleZ (Wisnioski et al. 2011), KLASS

**Table 1.** Properties of simulated galaxies in each redshift bin.

Redshift bin	Simulations	$M_*$ ( $10^{10} M_\odot$ )	SFR <sup>a</sup> ( $M_\odot \text{ yr}^{-1}$ )	$\sigma_{1D}$ <sup>b</sup> ( $\text{km s}^{-1}$ )	$\sigma_{1D, \text{median}}^c$ ( $\text{km s}^{-1}$ )	Number <sup>d</sup>
$0 \leq z < 0.25$	m	$2.58^{+0.82}_{-0.84}$	$4.8^{+2.0}_{-3.3}$	$16.0^{+4.7}_{-4.9}$	$119.0^{+10.0}_{-8.4}$	95
$0.25 \leq z < 0.5$	m	$1.71^{+0.39}_{-0.40}$	$4.3^{+1.3}_{-1.4}$	$25.0^{+7.2}_{-8.0}$	$125.5^{+11.5}_{-11.2}$	100
$0.5 \leq z < 1.0$	m	$1.17^{+0.28}_{-0.24}$	$5.0^{+1.3}_{-1.3}$	$34.8^{+12.1}_{-11.3}$	$121.2^{+15.7}_{-20.9}$	43
$1.0 \leq z < 1.5$	m	$0.71^{+0.11}_{-0.11}$	$6.7^{+3.0}_{-3.8}$	$50.1^{+11.7}_{-13.0}$	$71.3^{+20.1}_{-20.7}$	19
$1.5 \leq z < 2.0$	m	$0.31^{+0.15}_{-0.15}$	$4.4^{+3.2}_{-2.5}$	$39.2^{+8.8}_{-10.0}$	$67.0^{+18.4}_{-18.1}$	35
$2.0 \leq z < 2.5$	all	$0.29^{+0.14}_{-0.12}$	$5.9^{+3.6}_{-3.6}$	$44.0^{+16.1}_{-18.3}$	$87.4^{+26.0}_{-28.5}$	59
–	m	$0.14^{+0.05}_{-0.07}$	$2.9^{+1.1}_{-1.8}$	$35.8^{+1.0}_{-6.3}$	$58.9^{+11.6}_{-15.3}$	10
–	z2h	$0.31^{+0.18}_{-0.17}$	$6.3^{+3.6}_{-3.6}$	$47.3^{+20.1}_{-18.0}$	$90.5^{+28.6}_{-27.2}$	49
$2.5 \leq z < 3.0$	all	$0.20^{+0.10}_{-0.14}$	$7.1^{+5.5}_{-5.8}$	$46.0^{+13.8}_{-15.8}$	$84.3^{+28.8}_{-27.9}$	44
–	m	$0.10^{+0.01}_{-0.07}$	$4.6^{+2.1}_{-3.4}$	$47.2^{+6.0}_{-4.9}$	$72.4^{+16.0}_{-7.9}$	11
–	z2h	$0.24^{+0.06}_{-0.13}$	$7.9^{+5.8}_{-5.9}$	$43.8^{+14.2}_{-15.3}$	$87.0^{+26.1}_{-25.6}$	33
$3.0 \leq z < 3.5$	all	$0.08^{+0.03}_{-0.07}$	$3.1^{+3.0}_{-2.4}$	$40.4^{+16.3}_{-15.9}$	$73.9^{+24.2}_{-25.8}$	43
–	m	$0.03^{+0.01}_{-0.01}$	$1.3^{+0.2}_{-0.5}$	$31.1^{+2.6}_{-5.8}$	$53.3^{+5.9}_{-5.2}$	12
–	z2h	$0.10^{+0.07}_{-0.05}$	$4.2^{+4.8}_{-2.8}$	$43.6^{+20.0}_{-19.1}$	$86.1^{+34.7}_{-33.6}$	31

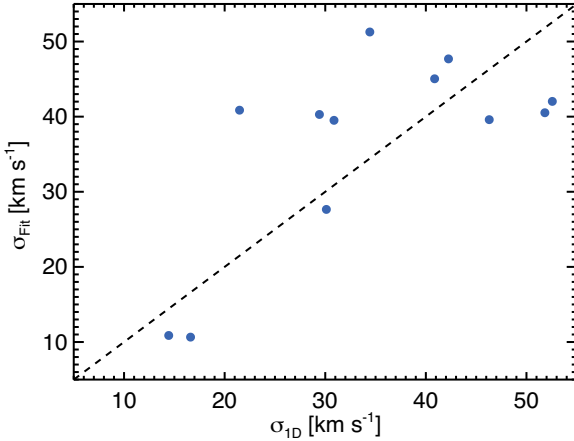
Notes. <sup>a</sup> Time-averaged SFR based on stars formed within the past 10 Myr.

<sup>b</sup>  $\sigma_{1D}$  is defined as the minimum value across  $10^4$  viewing angles.

<sup>c</sup>  $\sigma_{1D, \text{median}}$  is the median 1D velocity dispersion from all viewing angles. These values are significantly larger than  $\sigma_{1D}$  as they certainly include large-scale motions, such as rotation.

<sup>d</sup> The number of galaxy snapshots in each redshift bin with valid velocity dispersion measurements.

<sup>e</sup> The median value in each redshift bin; the quoted errors represent 16–84 per cent of the data in each redshift bin.



**Figure 2.**  $\sigma_{1D}$  (SFR-weighted standard deviation of the velocity distribution minimized over  $10^4$  viewing angles), which is intended to represent the observed velocity dispersion, versus  $\sigma_{\text{Fit}}$  (radially averaged velocity dispersion from the best-fitting tilted-ring models) for a subset of simulated galaxy snapshots that exhibit disc-like kinematics. The black dashed line indicates a one-to-one correlation. The proxy for velocity dispersion used in this work ( $\sigma_{1D}$ ) generally agrees with the velocity dispersion from detailed disc modelling, an approach used in recent IFS observational work.

(Mason et al. 2017), SHIZELS (Molina et al. 2016), CASSOWARY (Leethochawalit et al. 2016), SINS disc-like galaxies (Cresci et al. 2009), lensed galaxies (Livermore et al. 2015), the Law et al. (2009) OSIRIS survey, KDS (Turner et al. 2017), and VVDS (Lemoine-Busserolle et al. 2010). The kinematic properties derived from these surveys are based on nebular emission lines (e.g. H  $\alpha$ , [O III], and [O II]) and thus trace ionized gas.

We subtract a value of  $15 \text{ km s}^{-1}$  in quadrature from the velocity dispersion measured in these IFS surveys to account for the combination of thermal and non-thermal dispersion (Krumholz & Burkhardt 2016). This corrected velocity dispersion should be

roughly analogous to  $\sigma_{1D}$  of simulated galaxies, computed based on gas particles using an SFR weighting. Here, we only include measurements from IFS surveys (either AO-assisted or seeing-limited observations) that are based on spatially resolved velocity dispersion maps and are limited to including those studies that made their measurements available. We do not include dispersion measurements based on integrated spectra since they likely include bulk motions, such as rotation (e.g. Förster Schreiber et al. 2009). The median  $z$ ,  $M_*$  (when available), SFR (when available), and  $\sigma_{1D}$  values of the star-forming galaxies in each survey are summarized in Table 2. In addition to these IFS surveys, we supplement the  $z = 0$  data with H I and molecular gas surveys compiled by Krumholz et al. (2018, including data from Ianjamasimanana et al. 2012, Stilp et al. 2013, and local ULIRGs).

Fig. 3 illustrates the distribution of the simulated and observed galaxies in the SFR– $M_*$  plane, colour coded according to redshift. For the three haloes run to  $z = 0$ , a clear trend of increasing  $M_*$  with decreasing redshift is seen for the simulated galaxies as a direct result of continuous mass assembly over time. However, due to the small number of simulated galaxies analysed here, the dynamic range in  $M_*$  at a given redshift is significantly less than that spanned by the observed galaxies.

### 3.2 Observational diagnostics: $\sigma_{1D}$ as a function of $z$ and SFR

In this section, we examine whether the FIRE simulations exhibit the general trends in  $\sigma_{1D}$ ,  $z$ , and SFR present in the observations. Studies such as Wisnioski et al. (2015) and Turner et al. (2017) compiled surveys from literature and found that the trend of increasing intrinsic velocity dispersion with redshift is consistent with the expectation due to increased gas fraction. However, differences in survey designs and sample selections could potentially complicate the interpretation. To this end, Fig. 4 plots  $\sigma_{1D}$  as a function of redshift only using those observed galaxies and simulation snapshots that fall within the typical scatter ( $\pm 0.3$  dex) of the MS. About half

**Table 2.** Properties of observed galaxies.

Survey	Number <sup>a</sup>	Redshift <sup>b</sup>	Median $M_*$ ( $10^{10} M_\odot$ )	Median SFR ( $M_\odot \text{ yr}^{-1}$ )	Median $\sigma^c$ ( $\text{km s}^{-1}$ )	References
H I + molecular gas	56	$0.001\,08^{+0.00089}_{-0.00104}$	$0.06^{+0.73}_{-0.06}$	$0.48^{+1.62}_{-0.48}$	$11^{+3}_{-4}$	Compiled by Krumholz et al. (2018)
GHASP	137	$0.005\,08^{+0.00346}_{-0.00366}$	$1.10^{d+0.99}_{-1.07}$	$0.15^{d+0.28}_{-0.15}$	$19^{+5}_{-5}$	Epinat et al. (2008, 2010)
DYNAMO	67	$0.077\,22^{+0.05472}_{-0.02125}$	$1.62^{+1.40}_{-1.45}$	$8.3^{+7.6}_{-8.1}$	$38^{+18}_{-17}$	Green et al. (2014)
LBA	16	$0.18^{+0.02}_{-0.04}$	$0.63^{+0.37}_{-0.38}$	$19.4^{+0.6}_{-16.9}$	$65^{+7}_{-17}$	Gonçalves et al. (2010)
MUSE/KMOS disc	175	$0.81^{+0.28}_{-0.31}$	$0.24^{+0.61}_{-0.24}$	$3.3^{+5.0}_{-3.2}$	$43^{+12}_{-12}$	Swinbank et al. (2017)
KROSS	472	$0.84^{+0.06}_{-0.05}$	$0.98^{+0.76}_{-0.78}$	$7.0^{+4.1}_{-4.2}$	$41^{+19}_{-20}$	Harrison et al. (2017)
IROCKS	23	$0.94^{+0.09}_{-0.09}$	$3.16^{+1.85}_{-2.37}$	$11.1^{+9.4}_{-8.4}$	$60^{+5}_{-7}$	Johnson et al. (2017)
MASSIV	48	$1.23^{+0.17}_{-0.21}$	$1.51^{+2.20}_{-1.06}$	$45.9^{+23.3}_{-35.9}$	$50^{+24}_{-21}$	Mieda et al. (2016)
WiggleZ	13	$1.31^{+0.02}_{-0.02}$	$1.99^{+3.02}_{-1.36}$	$29.9^{+10.7}_{-9.7}$	$91^{+9}_{-8}$	Epinat et al. (2012); Queyrel et al. (2012)
KLASS	32	$1.41^{+0.36}_{-0.48}$	$0.54^{+0.22}_{-0.52}$	$6.2^{+3.6}_{-6.0}$	$52^{+33}_{-31}$	Wisnioski et al. (2011)
SHIZELS	19	... <sup>e</sup>	$1.07^{+0.92}_{-0.81}$	$7^{+3}_{-5}$	$70^{+19}_{-15}$	Mason et al. (2017)
CASSOWARY	11	$2.13^{+0.41}_{-0.10}$	... <sup>f</sup>	$36^{+23}_{-24}$	$59^{+5}_{-17}$	Swinbank et al. (2012a); Molina et al. (2016)
SINS disc-like	12	$2.21^{+0.18}_{-0.17}$	$3.80^{+2.80}_{-3.18}$	$100^{+46}_{-84}$	$50^{+6}_{-18}$	Leethochawalit et al. (2016)
Lensed	17	$2.21^{+0.44}_{-0.72}$	$0.32^{+0.68}_{-0.25}$	$5^{+6}_{-4}$	$58^{+10}_{-10}$	Cresci et al. (2009)
Law OSIRIS	16	$2.29^{+0.13}_{-0.14}$	$2.88^{+0.21}_{-2.58}$	$19^{+9}_{-6}$	$67^{+17}_{-13}$	Livermore et al. (2015)
KDS	32	$3.37^{+0.23}_{-0.27}$	$0.50^{+0.29}_{-0.40}$	$10.4^{+7.9}_{-7.4}$	$69^{+22}_{-21}$	Law et al. (2009)
VVDS	3	3.28, 3.28, 3.70	1.23, 1.62, 1.51	125, 427, 1257	70, 58, 76	Turner et al. (2017)
						Lemoine-Busserolle et al. (2010)

Notes. <sup>a</sup> The number of galaxies in each survey with valid velocity dispersion measurements.

<sup>b</sup> The errors in redshift,  $M_*$ , SFR, and  $\sigma_{\text{ID}}$  represent 16–84 per cent of the data in each survey.

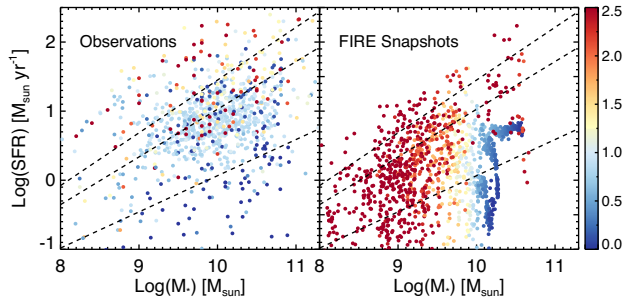
<sup>c</sup> The value  $15 \text{ km s}^{-1}$  has been subtracted in quadrature for  $\sigma$  of individual galaxies except for the H I survey.

This is to account for the combination of thermal and non-thermal dispersion (Krumholz & Burkhardt 2016).

<sup>d</sup> A subset of GHASP galaxies has  $M_*$  and SFR estimates from the MPA-JHU measurements based on SDSS DR8 spectra (Kauffmann et al. 2003; Brinchmann et al. 2004; Salim et al. 2007).

<sup>e</sup> SHIZELS is comprised of galaxies in three redshift bins:  $z \sim 0.8$ , 1.47, and 2.23.

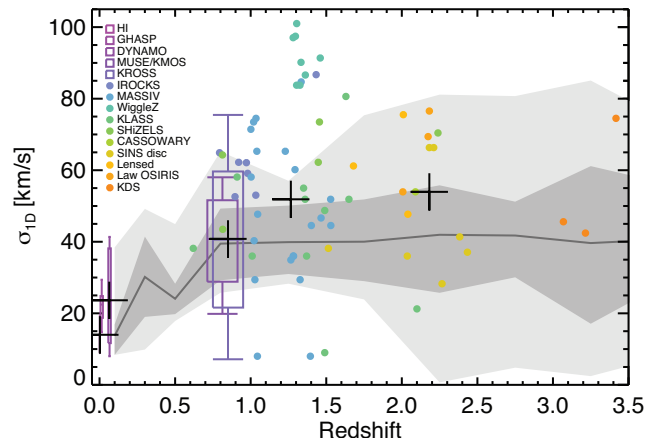
<sup>f</sup> Typical  $\text{Log}(M_*) = 9.0$ – $9.6$ .



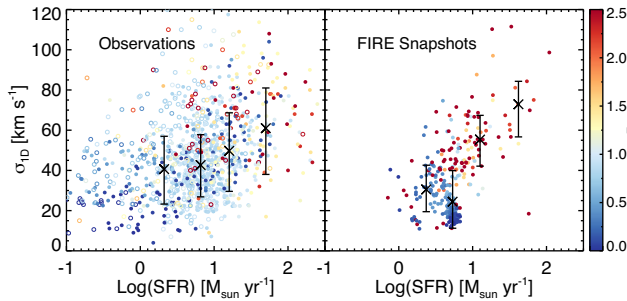
**Figure 3.** Distribution of the observed and simulated galaxies in the SFR– $M_*$  plane, colour coded according to redshift. The simulated galaxies include all snapshots of the 10 simulations (sampled every few tens of Myr) that fall on or above the galaxy MS. The SFRs shown in the right panel correspond to the time-averaged SFR calculated based on stars formed within the past 10 Myr. The three dashed lines from bottom to top indicate the star-forming galaxy MS at  $z = 0.15$ , 1, 2.2 from Speagle et al. (2014). The observed and simulated galaxies broadly overlap. In the simulations, the apparent trend of increasing stellar mass with redshift is an artefact of analysing only three haloes run to  $z = 0$ , all of which have  $z = 0$  halo masses of  $\sim 10^{12} M_\odot$ .

of the observed galaxies are not included in this plot because they fall above or below the MS.

The median  $\sigma_{\text{ID}}$  values of the simulated galaxies differ by  $\sim 10 \text{ km s}^{-1}$  from those of the observed galaxies, and the simulated galaxies have systematically lower median values at  $z > 1$ . This systematic offset may be a result of several factors: the fact that  $\sigma_{\text{ID}}$  cannot perfectly replicate the measured intrinsic velocity dispersion, the imperfect (or lack of) beam-smearing corrections



**Figure 4.**  $\sigma_{\text{ID}}$  as a function of redshift for main-sequence galaxies. The dark grey solid line shows the median value for the simulated galaxies that lie on the star-forming galaxy MS within redshift bins of width  $\Delta z = 0.2$  ( $z < 1$ ) or  $\Delta z = 0.5$  ( $z > 1$ ), and the lighter (lightest) grey coloured area encloses 68 per cent (95 per cent) of the data. The simulated galaxies include all snapshots of the 10 simulations sampled every few tens of Myr. Each box plot or set of coloured circles represents the MS galaxies from a given observational survey, as labelled in the legend. The mixed representation of coloured circles and box plots was chosen for clarity. In each box plot, the middle bar corresponds to the median  $\sigma_{\text{ID}}$ , and the boxes and vertical bars encompass 68 and 95 per cent of the data, respectively. The width of each box is proportional to the redshift coverage of the survey. The black crosses represent the median  $\sigma_{\text{ID}}$  of the observed galaxies that fall on the galaxy MS in five redshift bins:  $z < 0.1$ ,  $0.1 < z < 0.3$ ,  $0.7 < z < 1.0$ ,  $1.0 < z < 1.5$ , and  $2.0 < z < 2.5$ .

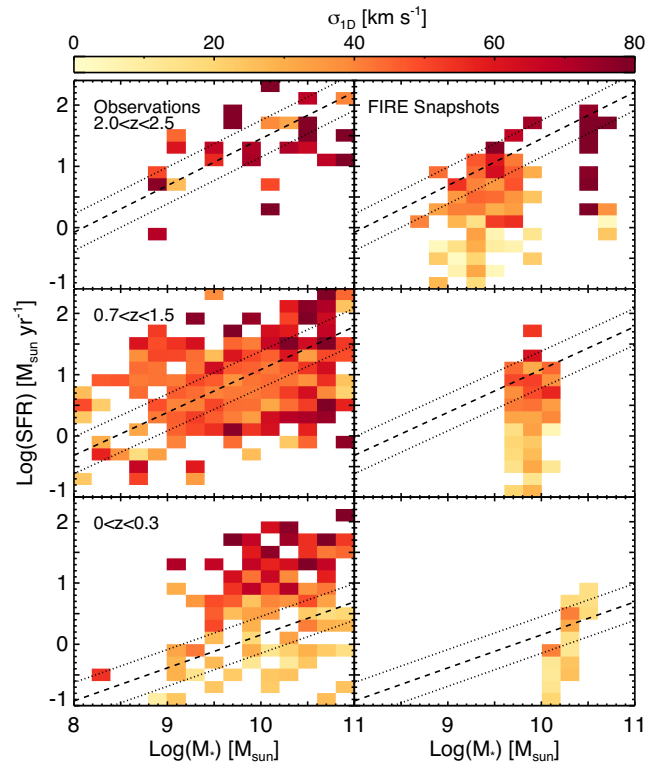


**Figure 5.** Distributions of the observed and simulated galaxies in the  $\sigma_{\text{ID}}$ –SFR plane, coloured coded according to redshift. The open circles in the observations panel indicate galaxies that fall below the galaxy MS. The black x’s and error bars overlaid on the data points represent the median  $\sigma_{\text{ID}}$  and 68 percent distribution of the galaxies that lie on or above the MS in four log(SFR) bins. The simulations and observations both exhibit positive correlations between  $\sigma_{\text{ID}}$  and SFR.

in the IFS measurements (e.g. Stott et al. 2016; Pineda et al. 2017), and/or differences in physical properties such as SFR and  $M_*$  (Fig. 3). Regardless, MS galaxies from both observations and simulations have median  $\sigma_{\text{ID}}$  values that increase from  $z \sim 0$  to  $z \sim 1$ –1.5, but the increasing trend is less evident at higher redshift. The increasing trend from  $z \sim 0$  to 1 is consistent with the results of Kassin et al. (2014), who analysed the evolution of the velocity dispersion traced by cold and warm gas in a suite of cosmological zoom simulations.

Fig. 5 shows the distribution of  $\sigma_{\text{ID}}$  and SFR for the observed and simulated galaxies. For the observed galaxies, a positive correlation is seen out to  $z \lesssim 1$ , consistent with the results of Green et al. (2014). No obvious offset is seen in the  $\sigma_{\text{ID}}$ –SFR relation within the redshift range probed. However, it is less clear whether the same positive correlation extends to  $z \gtrsim 2$  galaxies owing to the small number of galaxies. The star-forming galaxies (galaxies that lie on or above the MS) from the FIRE simulations also exhibit a positive correlation between  $\sigma_{\text{ID}}$  and SFR, consistent with the observed galaxies. There is also no obvious offset in the  $\sigma_{\text{ID}}$ –SFR relations at different redshifts except for a group of low-redshift snapshots from the m12i simulation that lie significantly below the relations.

Although the FIRE simulations reproduce the observed trends in the  $\sigma_{\text{ID}}$ – $z$  and  $\sigma_{\text{ID}}$ –SFR planes, understanding what physical processes are responsible for these trends remains challenging. First, the interpretation that velocity dispersion increases with redshift is tangled with the positive correlation between  $\sigma_{\text{ID}}$  and SFR, given that galaxies targeted by IFS surveys at  $z \gtrsim 1$  tend to have higher SFRs compared with galaxies targeted by lower redshift IFS surveys. Secondly, the  $\sigma_{\text{ID}}$  values of the observed galaxies exhibit large scatter even after taking into account the differences in SFR and removing galaxies that fall below the MS, suggesting that star formation is not the only relevant driver of velocity dispersion (although this interpretation can be complicated if the SFR and  $\sigma_{\text{ID}}$  vary on short time-scales and are not perfectly synchronized; this is explored in detail below). The scatter in the  $\sigma_{\text{ID}}$ –SFR relation likely cannot be attributed to different techniques or definitions used in each survey given that there is a similarly large scatter in the simulated galaxies. Several previous works have examined the relationship between velocity dispersion and SFR surface density ( $\Sigma_{\text{SFR}}$ ) because such a relation may naturally arise from the scaling between  $\Sigma_{\text{SFR}}$  and gas surface density ( $\Sigma_{\text{gas}}$ ) in marginally stable



**Figure 6.** Distributions of the observed and simulated galaxies in the SFR– $M_*$  plane in three redshift bins ( $2 < z < 2.5$ ,  $0.7 < z < 1.5$ , and  $0 < z < 0.3$ ), colour coded according to  $\sigma_{\text{ID}}$ . Each small  $M_*$  and SFR bin [ $\Delta \log(M_*) = 0.2$  and  $\Delta \log(\text{SFR}) = 0.2$ ] is colour coded based on the median  $\sigma_{\text{ID}}$  values for all galaxies within the bin. The three dashed lines in the top, middle, and bottom panels indicate the star-forming galaxy MS at  $z = 2.2$ , 1.1, 0.15, and the dotted lines represent the  $\pm 0.3$  dex scatter. In some panels,  $\sigma_{\text{ID}}$  tends to increase with SFR, whereas in others,  $\sigma_{\text{ID}}$  seems to be correlated in  $M_*$ , and in other panels, no clear trend is observed. It is worth noting that especially at  $z > 2$ , the simulations cover galaxies well below the MS, unlike the observed galaxy samples, likely because of observational selection effects.

discs (Swinbank et al. 2012b). However, the  $\sigma_{\text{ID}}$ – $\Sigma_{\text{SFR}}$ <sup>5</sup> relation of the FIRE galaxies exhibits a comparably large scatter as seen in the  $\sigma_{\text{ID}}$ –SFR relation.

### 3.3 Distribution of $\sigma_{\text{ID}}$ in the SFR– $M_*$ plane

In Fig. 6, we plot the distribution of  $\sigma_{\text{ID}}$  in the SFR– $M_*$  plane for both observed and simulated galaxies in three redshift bins. These figures demonstrate that how  $\sigma_{\text{ID}}$  depends on galaxy properties and varies with redshift, thus complicating interpretation of these results. Whereas  $\sigma_{\text{ID}}$  tends to increase with SFR in the lowest redshift panel for the observed galaxies and the two higher redshift panels for the simulated galaxies, this trend with SFR is less evident for the observed galaxies in the two higher redshift bins. Another possible trend of increasing  $\sigma_{\text{ID}}$  with  $M_*$  has been reported in Stott et al. (2016), but this trend no longer exists (or exists only at the high-mass end for the full sample) in the updated analysis in Johnson et al. (2017). This is evident in the  $0.7 < z < 1.5$  panel for the observed galaxies and the  $2.0 < z < 2.5$  panel for the simulated

<sup>5</sup>Here, we estimate  $\Sigma_{\text{SFR}}$  of the FIRE galaxies as  $\text{SFR}/A$ , where  $A$  is the area calculated based on an effective radius that encloses half of the total SFR.



galaxies. This potential trend with  $M_*$  suggests that variations in  $M_*$  within samples may contribute to the large scatter in the  $\sigma_{\text{ID}}$ –SFR relation of a given sample. However, no clear trend with  $M_*$  is seen in any other panel.

Finally, whereas most observed galaxies with  $\text{SFR} \gtrsim 10 \text{ M}_\odot \text{ yr}^{-1}$  at all redshifts have  $\sigma_{\text{ID}} \gtrsim 50 \text{ km s}^{-1}$ , there is a clear discrepancy between the  $0 < z < 0.3$  and  $0.7 < z < 1.5$  bins for the lower SFR galaxies. For  $\text{SFR} \lesssim 10 \text{ M}_\odot \text{ yr}^{-1}$ , galaxies at  $z \sim 1$  have higher  $\sigma_{\text{ID}}$  than their lower redshift counterparts at a given SFR and  $M_*$ . Although the overlap in SFR and  $M_*$  is limited for the simulated galaxies in different redshift bins, a slight increase in  $\sigma_{\text{ID}}$  with redshift is seen in the regions of overlap between the  $z \sim 2$  and 1 panels and between the  $z \sim 1$  and 0 panels. These results suggest that for at least some (lower SFR) galaxies, the intrinsic velocity dispersion varies with redshift even for galaxies with similar  $M_*$  and SFR.

#### 4 PHYSICAL DRIVERS OF KINEMATIC EVOLUTION

To gain further insight into the physical drivers of galaxy dynamics, we analyse the time evolution of various physical properties of the individual central galaxies of each halo. Figs 7 and 8 show the time evolution of  $\sigma_{\text{ID}}$ , SFR, gas inflow rate ( $\dot{M}_{\text{gas}}$ ), gas fraction ( $f_{\text{gas}}$ ), and  $M_*$  of the three m-series and seven z2h simulations, respectively. Several recent studies have investigated the star formation, gas accretion, and mass assembly histories of these FIRE simulations in detail (e.g. Hopkins et al. 2014; Muratov et al. 2015; Anglés-Alcázar et al. 2017; Sparre et al. 2017). In these simulations, the gas inflow rate varies on time-scales of a few 100 Myr. Although several major mergers lead to dramatic increases in  $\dot{M}_{\text{gas}}$ , minor mergers and smooth gas accretion, partially due to galactic fountains, predominantly govern the amount of material for subsequent star formation. The SFRs of these galaxies are highly dynamic, and individual galaxies can evolve through quiescent and star-forming phases within a few 100 Myr (Sparre et al. 2017). The gas fractions vary on similar time-scales as SFR and  $\dot{M}_{\text{gas}}$  whereas  $M_*$  tends to vary on longer time-scales. Recall that the gas fraction is computed as the ratio of the dense ( $n \geq 1 \text{ cm}^{-3}$ ) gas mass to the total stellar and dense gas mass within  $0.2 R_{\text{vir}}$ . We note that the behaviour of gas fractions can change significantly depending on the density threshold that we employ. A lower or even no threshold would likely include a significant amount of gas outside of the ISM/galaxy disc (i.e. the circumgalactic medium, including gas in galactic fountains; Muratov et al. 2015; Anglés-Alcázar et al. 2017); consequently, the gas mass in the ISM may exhibit short or long time-scale variations that are not reflected in other gas fraction measures. The gas fraction in the ISM/disc is the relevant quantity for self-regulated star formation models (e.g. Thompson et al. 2005; Ostriker & Shetty 2011; Faucher-Giguère et al. 2013; Hayward & Hopkins 2017). A more detailed comparison with the predictions of such models should use a proxy that better represents the disc fraction, but we defer such a comparison to future work and simply advise that the time evolution of the gas fraction plotted here should be interpreted with the above caveat in mind.

Among the properties shown in Figs 7 and 8, the time evolutions of SFR and  $\dot{M}_{\text{gas}}$  most closely resemble the variations in  $\sigma_{\text{ID}}$ ; all three properties vary significantly on time-scales of  $< 100$  Myr. By definition,  $\sigma_{\text{ID}}$  approaches zero at low SFR ( $\text{SFR} \lesssim 1 \text{ M}_\odot \text{ yr}^{-1}$ ), since only a few SPH gas particles with non-zero SFRs are available to trace the galaxy dynamics. In general, such time periods also correspond to when galaxies have lower gas inflow rates. Increases

in  $\sigma_{\text{ID}}$  occur near enhancements in  $\dot{M}_{\text{gas}}$  and SFR, although not exactly simultaneously. The approximate temporal correspondence of variations in  $\sigma_{\text{ID}}$  and SFR is reflected in the positive SFR– $\sigma_{\text{ID}}$  correlation, and the fact that peaks do not exactly coincide in time may be responsible for the large scatter in this relation (Fig. 5). The similarities between the evolutions of SFR,  $\sigma_{\text{ID}}$ , and  $\dot{M}_{\text{gas}}$  suggest that variations in velocity dispersion, star formation (and thus prompt stellar feedback), and gas inflow are all related.

To examine whether the similarities in the temporal evolutions of SFR,  $\sigma_{\text{ID}}$ , and  $\dot{M}_{\text{gas}}$  are indicative of any causal effects, we measure the time delays between pairs of these three quantities by cross-correlating their time series. Because these zoom-in simulations have unequal time intervals, we first bin and interpolate these time series with a uniform sampling rate determined based on the mean time interval of the entire time series ( $\sim 34$  Myr for the m-series and  $\sim 17$  Myr for the z2h simulations). For each simulation suite, we calculate temporal cross-correlation functions of pairs of time series  $[(x, y) = (\dot{M}_{\text{gas}}, \text{SFR}), (\dot{M}_{\text{gas}}, \sigma_{\text{ID}}), \text{ and } (\sigma_{\text{ID}}, \text{SFR})]$  that are normalized to have means of 0 and variances of 1,  $\text{CCF}(\tau_k) = \frac{1}{N} \sum_{i=1}^{N-k} x_i y_{i+k}$ , where  $i$  indicates the time bin,  $N$  is the total number of time bins,  $\tau_k$  is the lag corresponding to the  $k$  time bin, and  $k$  is varied to probe lags from  $-500$  to  $500$  Myr. Table 3 summarizes the time-delay measurements  $[\tau(\dot{M}_{\text{gas}}\text{--SFR}), \tau(\dot{M}_{\text{gas}}\text{--}\sigma_{\text{ID}}), \tau(\sigma_{\text{ID}}\text{--SFR})]$  by taking the peak value of  $\text{CCF}(\tau_k)$  within a  $\pm 500$  Myr. Values in Table 3 marked with an ‘\*’ are not robust because there are multiple comparable peaks within a  $\pm 500$  Myr window.

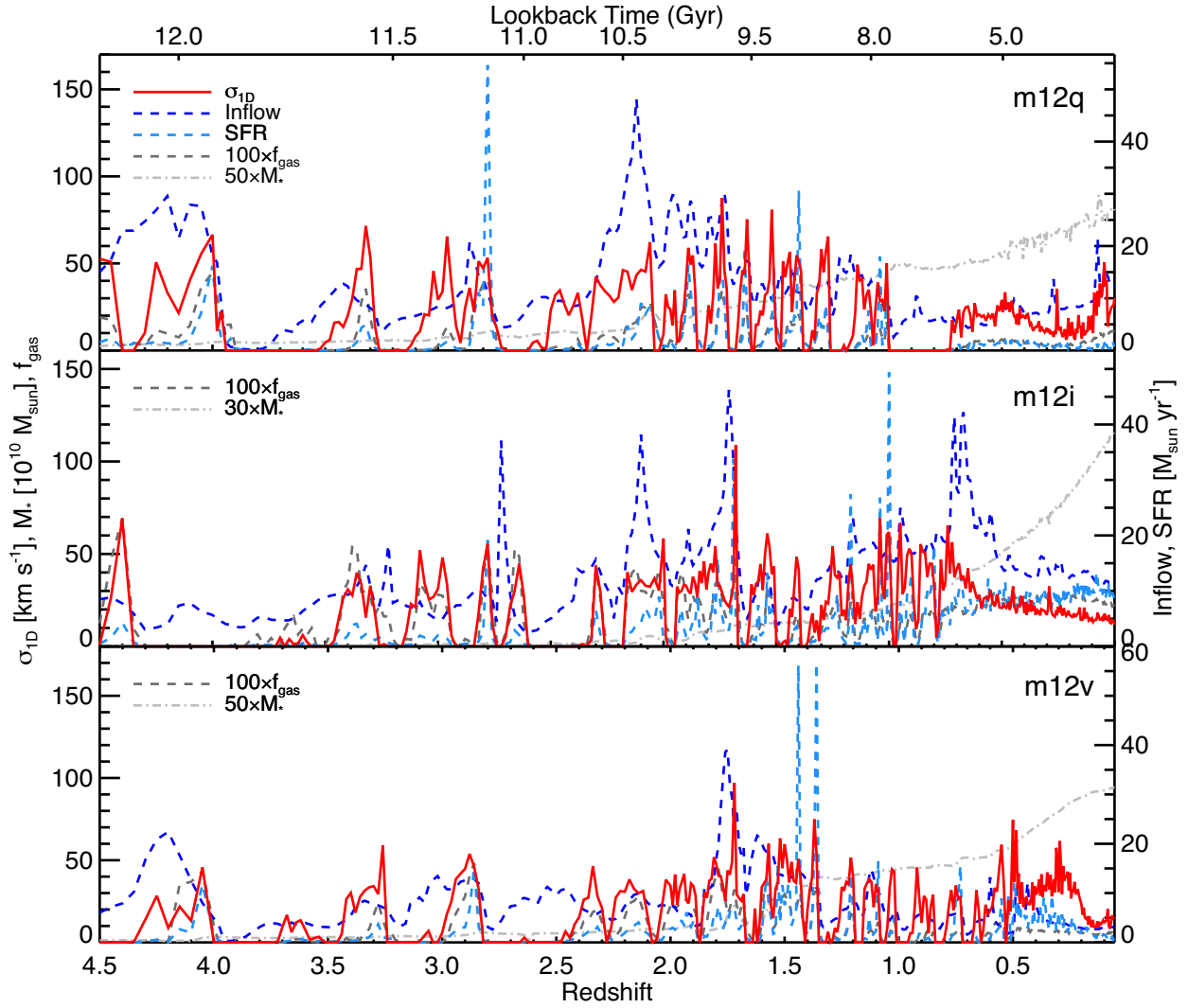
We note that the absolute values of these time-delay measurements can change by a factor of a few when employing different time sampling rates. However, the signs of these time-delay measurements are relatively stable. In general, variations in  $\dot{M}_{\text{gas}}$  occur prior to variations in SFR, suggesting that inflows through  $0.2 R_{\text{vir}}$ , due to cosmological gas inflow or galactic fountains, lead to subsequent enhanced star formation activity. As expected, the relation between  $\dot{M}_{\text{gas}}$  and SFR becomes weaker if we define the inflow rate as the mass infalling through a shell with a radius of  $1 R_{\text{vir}}$ . Negative signs for  $\tau(\dot{M}_{\text{gas}}\text{--}\sigma_{\text{ID}})$  or  $\tau(\sigma_{\text{ID}}\text{--SFR})$  are obtained for a few simulated galaxies, suggesting that enhancements in velocity dispersion may occur after enhancements in the gas inflow rate at  $0.2 R_{\text{vir}}$  but before the SFR is enhanced. However, these trends are less robust because positive or zero time delays are also obtained for some simulated galaxies. Given that the absolute values of  $\tau(\dot{M}_{\text{gas}}\text{--}\sigma_{\text{ID}})$  and  $\tau(\sigma_{\text{ID}}\text{--SFR})$  are typically less than the resolution of the time series, we can only conclude that variations in  $\sigma_{\text{ID}}$  roughly temporally coincide with variations in  $\dot{M}_{\text{gas}}$  and SFR. On a related note, El-Badry et al. (2016, 2017) investigated the stellar kinematics of low-mass galaxies from the FIRE project and found that the stellar velocity dispersion is strongly correlated with SFR, with an  $\sim 50$  Myr time delay. They attribute this correlation to both the SFR and stellar velocity dispersion being affected by stellar feedback and the consequent gas outflows.

## 5 DISCUSSION

### 5.1 Comparison with previous work

Several previous works have developed models that aim to examine the roles of gas accretion, gravitational instabilities, stellar feedback, and other physical processes in driving the enhanced velocity dispersions of high- $z$  galaxies. Comparisons between models and observations can provide some insights into the physical drivers since



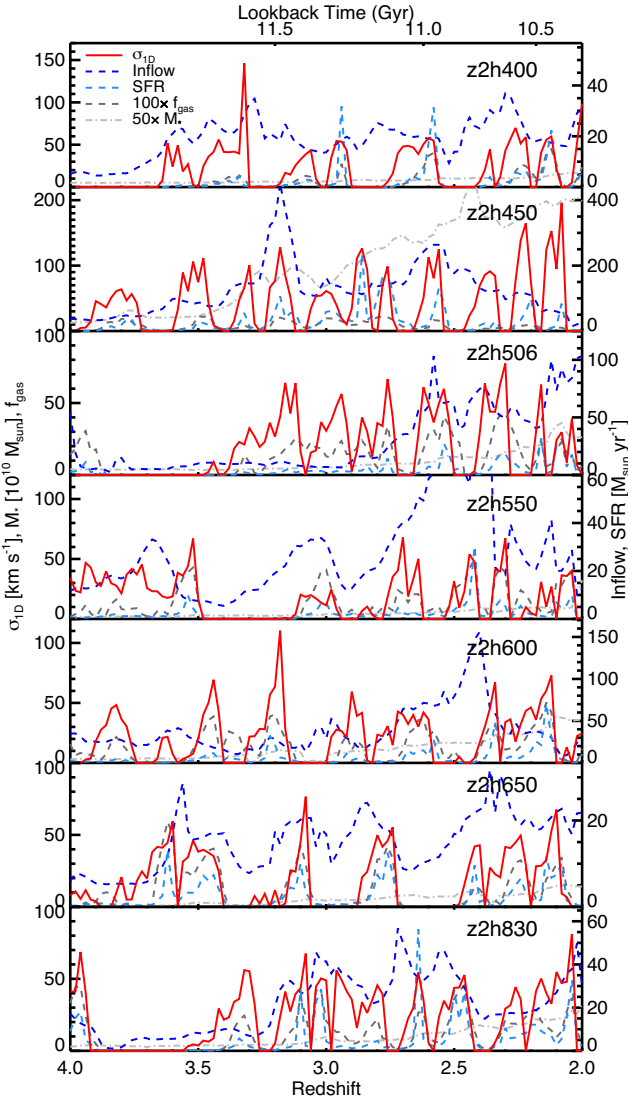


**Figure 7.** Time evolution of  $\sigma_{1D}$  (red solid lines), instantaneous SFR (light blue dashed lines), gas inflow rate ( $\dot{M}_{\text{gas}}$ , blue dashed lines),  $f_{\text{gas}}$  (dark grey dashed lines), and  $M_*$  (grey dash-dotted lines) for the three m-series simulations.  $f_{\text{gas}}$  is defined as the ratio of the ‘dense’ gas mass ( $n \geq 1 \text{ cm}^{-3}$ ) to the sum of the gas and stellar masses within  $0.2 R_{\text{vir}}$ .  $\dot{M}_{\text{gas}}$  is defined as the instantaneous mass flux through a thin spherical shell with an outer radius  $0.3 R_{\text{vir}}$  and inner radius  $0.2 R_{\text{vir}}$ . The values of  $f_{\text{gas}}$  and  $M_*$  are arbitrarily scaled (as indicated in the legend) for clarity, and the values of  $\dot{M}_{\text{gas}}$  and SFR are shown on the right axis.  $\sigma_{1D}$ , SFR, and  $\dot{M}_{\text{gas}}$  vary drastically on short ( $< 100 \text{ Myr}$ ) time-scales owing to stellar feedback-driven burstiness and stochasticity in gas inflow, which is partially due to galactic fountains. It is clear that peaks in  $\sigma_{1D}$ ,  $\dot{M}_{\text{gas}}$ , and SFR tend to temporally coincide but are not exactly simultaneous. The times at which  $\sigma_{1D}$  approaches zero correspond to times when few star-forming gas particles are present in the simulations.

these models predict different relationships between  $\sigma$  and other physical parameters. For example, simply requiring a marginally stable disc with Toomre  $Q$  parameter  $\approx 1$ , we expect  $\sigma \propto f_{\text{gas}}$  (e.g. Thompson et al. 2005; Faucher-Giguère et al. 2013), with no (additional) dependence on SFR [this *does not* preclude a correlation between  $\sigma_{1D}$  and SFR because all else being equal, owing to the Kennicutt–Schmidt relation (Schmidt 1959; Kennicutt 1998), SFR and  $f_{\text{gas}}$  should be correlated]. Krumholz & Burkert (2010) argue that in the steady-state configuration of the gravity-driven, turbulent disc model from Krumholz & Burkert (2010),  $\text{SFR} \propto f_{\text{gas}}^2 \sigma$ . This work also argues that models in which stellar feedback drives turbulence and ‘self-regulates’ galaxy-scale star formation (e.g. Thompson et al. 2005; Ostriker & Shetty 2011; Shetty & Ostriker 2012; Faucher-Giguère et al. 2013; Hayward & Hopkins 2017) predict a relation of  $\text{SFR} \propto \sigma^2$  with no dependence on  $f_{\text{gas}}$  (equation 8

of Krumholz & Burkert 2016), but cf. Ostriker & Shetty (2011) and Hayward & Hopkins (2017) for alternative interpretations. A recent work by Krumholz et al. (2018) summarizes the relations between SFR and  $\sigma$  under the effects of feedback and/or gravitational instability.

In principle, the FIRE simulations directly include the relevant processes (e.g. gravitational instability, gas inflow, and stellar feedback-driven turbulence), and the similarities between the  $\sigma_{1D}$ , SFR, and  $\dot{M}_{\text{gas}}$  time series demonstrated in Section 4 may indicate that one or both of these proposed mechanisms are at work. A positive correlation between SFR and  $\sigma_{1D}$ , consistent with the expectations of both gravity- and feedback-driven turbulence models, is seen in both observations and FIRE simulations (Fig. 5). The time variation of  $f_{\text{gas}}$  resembles that of the SFR (Figs 7 and 8), and thus we may expect some dependence between  $f_{\text{gas}}$  and  $\sigma_{1D}$  as well.



**Figure 8.** Time evolution of  $\sigma_{1D}$  (red solid lines), instantaneous SFR (light blue dashed lines),  $\dot{M}_{\text{gas}}$  (blue dashed lines),  $f_{\text{gas}}$  (dark grey dotted lines), and  $M_*$  (grey dash-dotted lines) of the seven z2h simulations. The values of  $f_{\text{gas}}$  and  $M_*$  are arbitrary scaled (as indicated in the legend) for clarity, and the values of  $\dot{M}_{\text{gas}}$  and SFR are shown on the right axis. These higher mass galaxies simulated only to  $z = 2$  exhibit the same qualitative behaviour as the lower mass galaxies shown in Fig. 7.

However, we caution against a direct comparison of this dependence with analytic models because in many snapshots (especially at high redshift), the star-forming gas does not exhibit disc-like kinematics, which is inconsistent with the assumptions of many analytic models. Moreover, as discussed above, the definition of  $f_{\text{gas}}$  in this work is not completely analogous to that in the aforementioned models. Finally, the significant time variability in, e.g. SFR implies that such quasi-steady-state models may only hold in a time-averaged sense; see Hayward & Hopkins (2017), Torrey et al. (2017), and Faucher-Giguère (2018) for further details.

Some analytic models have argued that accretion energy itself is unable to drive turbulence for longer than a characteristic accretion time (of the order of a few hundred Myr; e.g. Elmegreen & Burkert 2010), but others have argued that the following inflow within the

**Table 3.** Time-delay measurements for the simulations.

Simulation	Range (Gyr)	$\tau(\dot{M}_{\text{gas}}-\text{SFR})^a$ (Myr)	$\tau(\dot{M}_{\text{gas}}-\sigma_{1D})$ (Myr)	$\tau(\sigma_{1D}-\text{SFR})$ (Myr)
m12q	0–12	−69 <sup>b</sup>	0	0
m12i	0–12	−100	0	−34
m12v	0–12	−34	−35	0
z2h400	10.5–12	331*	0*	−17
z2h450	10.5–12	−331*	488*	0
z2h506	10.5–12	−52	418	0*
z2h550	10.5–12	−87	−87	0
z2h600	10.5–12	−348	−348	0
z2h650	10.5–12	−296*	−35	0
z2h830	10.5–12	−70	104*	0

*Notes:* <sup>a</sup>Time-delay measurements based on cross-correlation analyses between gas inflow rate and instantaneous SFR [ $\tau(\dot{M}_{\text{gas}}-\text{SFR})$ ], gas inflow rate and  $\sigma_{1D}$  [ $\tau(\dot{M}_{\text{gas}}-\sigma_{1D})$ ], and  $\sigma_{1D}$  and instantaneous SFR [ $\tau(\sigma_{1D}-\text{SFR})$ ].

<sup>b</sup>Peak value in the  $\pm 500$  Myr window.

\*Multiple comparable peaks within the  $\pm 500$  Myr window.

disc can drive turbulence for much longer (Genel et al. 2012). Moreover, an important characteristic of the simulated galaxies is that  $\sigma$  can vary significantly on time-scales of  $< 100$  Myr, including ‘gaps’ of comparable time for which  $\sigma$  of the star-forming gas is not traceable owing to a lack of star-forming gas particles.<sup>6</sup> This is in part due to the onset of stellar feedback processes such as radiation pressure, stellar winds, and supernovae, which can disrupt dense clumps and expel a significant fraction of the ISM (Muratov et al. 2015; Hayward & Hopkins 2017), causing star formation to temporarily cease and thus making it impossible to trace the gas kinematics via nebular emission lines. In this situation, mechanisms that can drive enhancements in the velocity dispersion of star-forming gas do not necessarily need to maintain enhanced velocity dispersions over time-scales longer than a few hundred Myr. Thus, we cannot rule out the importance of accretion in driving  $\sigma$  simply because the impact of accretion may be relatively short-lived. Overall, our results demonstrate the difficulty of inferring the physical driver(s) of velocity dispersion from integrated measurements, such as the global SFR, mainly because enhancements in  $\sigma_{1D}$ ,  $\dot{M}_{\text{gas}}$ , and SFR are not perfectly temporally coincident, which results in a significant *physical* scatter in the relationships amongst these quantities.

## 5.2 Observational implications and future work

In this section, we discuss several directions for future work. First, whereas in this work, we derive a single SFR-weighted  $\sigma$  for individual galaxies when analysing the simulations and comparing them with observations, we can extend this analysis to spatially resolved  $\sigma$ , SFR, and  $\dot{M}_{\text{gas}}$  maps and then compare the simulations with a subset of AO-assisted IFS observations with kpc-scale resolution. Previous high-resolution observations (at  $\sim 1$  kpc scales) have revealed a mixed association between the highest  $\sigma$  values and local maxima in the star formation surface density. For example, Genzel et al. (2011) argue that local star formation feedback does not directly drive the velocity dispersion given the weak dependence between  $\sigma$  and star formation surface density. However, Oliva-Altamirano et al. (2018) show that a subset of DYNAMO galaxies has local  $\sigma$  peaks that occur within 1 kpc of star-forming

<sup>6</sup>This can occur if no gas particles satisfy the criteria for star formation used in the FIRE simulations; see Section 2.1.

clumps, suggesting that stellar feedback does play some role, in addition to other drivers of turbulence. While the dominant scale on which stellar feedback drives turbulence is of the order of the disc scale height ( $\lesssim 1$  kpc) (Hayward & Hopkins 2017), different physical drivers may be relevant on different scales or/and in different physical regimes (e.g. at different gas surface densities). Searching for correlations among  $\sigma$ , SFR, and tracers of other potential drivers of local turbulence in high-resolution simulations may thus provide further insight into the physical interpretation of spatially resolved observations.

Our analysis demonstrates the importance of gas accretion in driving enhancements in velocity dispersion – perhaps indirectly by driving enhancements in the SFR and thus stellar feedback – but it is extremely challenging to directly probe the relationship between inflow and galaxy kinematics observationally. Although current observational constraints on  $\dot{M}_{\text{gas}}$  are limited to only a few candidate galaxies, examples such as that presented by Bouché et al. (2013) are intriguing given that their  $\dot{M}_{\text{gas}}$  estimate of  $\sim 30\text{--}60 M_{\odot} \text{ yr}^{-1}$  at 26 kpc from the galaxy centre is comparable to the inflow rates of most of the simulated galaxies studied in this work, and such  $\dot{M}_{\text{gas}}$  rates are indeed reasonable for galaxies with  $\sigma_{\text{ID}} \gtrsim 50 \text{ km s}^{-1}$ .

Moreover, individual galaxies in the FIRE simulations experience multiple phases with no ongoing star formation (although some low level of star formation may occur if the galaxies were simulated at higher resolution) with untraceable  $\sigma_{\text{ID}}$ . These galaxies can still have high  $f_{\text{totalgas}}$  values (based on the total gas mass in the simulations) and are only temporarily quenched and likely to rejuvenate within a few hundred Myr. If such periods are indeed important evolutionary phases of galaxies, then there would be a population of high- $f_{\text{totalgas}}$  galaxies with low SFR that would not be included in most IFS surveys because they would be undetected or have too low signal-to-noise ratios for detailed kinematic analysis. Future IFS surveys that can probe stellar kinematics of high- $z$  galaxies are thus critical for probing the kinematic evolution of galaxies in all evolutionary phases.

## 6 CONCLUSIONS

We investigate the origin of enhanced gas velocity dispersion ( $\sigma_{\text{intr}}$ ) of high-redshift star-forming galaxies using a suite of cosmological simulations from the FIRE-1 project. We define a measure of  $\sigma_{\text{ID}}$ , the minimum SFR-weighted standard deviation computed over  $10^4$  viewing angles, that aims to be representative of  $\sigma_{\text{intr}}$  for observed galaxies. In parallel, we compile a set of  $\sigma_{\text{intr}}$  measurements of  $0 \leq z \lesssim 3$  star-forming galaxies from IFS surveys that probe the kinematics of ionized gas, and we systematically compare these observations with the simulated galaxies from the FIRE-1 project. Our primary conclusions are summarized as follows:

- (i) In both observations and simulations, galaxies on the star-forming MS have median  $\sigma_{\text{ID}}$  values that increase from  $z \sim 0$  to  $z \sim 1\text{--}1.5$ , but this increasing trend is less evident at higher redshift.
- (ii) The simulated galaxies exhibit a positive correlation between  $\sigma_{\text{ID}}$  and SFR, as is also evident in the observations. In both the observed and simulated galaxy samples, there is no obvious offset in the  $\sigma_{\text{ID}}$ –SFR relations at different redshifts.
- (iii) The large scatter in the  $\sigma_{\text{ID}}$ –SFR relation suggests that either stellar feedback is not the only relevant driver of enhanced velocity dispersion or that the slight asynchronicity of the enhancements in  $\sigma_{\text{ID}}$  and SFR results in a large physical scatter in this relation.

- (iv) A possible correlation of  $\sigma_{\text{ID}}$  with  $M_*$ , which is seen in the observed galaxies at  $z \sim 1$  and the FIRE simulations at  $z \gtrsim 2$ , suggests that differences in  $M_*$  at a fixed SFR may contribute to the scatter in the  $\sigma_{\text{ID}}$ –SFR relation.

- (v) Based on an analysis of the time evolution of individual simulated galaxies’ physical and kinematic properties (SFR,  $M_*$ ,  $\dot{M}_{\text{gas}}$ ,  $f_{\text{gas}}$ , and  $\sigma_{\text{ID}}$ ), we find that the variations in SFR,  $\dot{M}_{\text{gas}}$ , and  $f_{\text{gas}}$  are approximately temporally coincident with variations in  $\sigma_{\text{ID}}$ , whereas  $M_*$  varies on longer time-scales. SFR,  $\dot{M}_{\text{gas}}$ , and  $\sigma_{\text{ID}}$  can all vary significantly on time-scales of  $< 100$  Myr, especially at high redshift ( $z \gtrsim 1$ ).

- (vi) We measure the time delay between pairs of the three properties SFR,  $\dot{M}_{\text{gas}}$ , and  $\sigma_{\text{ID}}$  by cross-correlating their time series. A robust negative time delay between  $\dot{M}_{\text{gas}}$  and SFR is found (i.e. peaks in  $\dot{M}_{\text{gas}}$  tend to proceed peaks in SFR), thus suggesting that variations in the gas inflow rate through a shell of radius  $0.2 R_{\text{vir}}$ , due either to cosmological inflow or galactic fountains, lead to subsequently enhanced SFR. The small time delays measured between  $\dot{M}_{\text{gas}}$  and  $\sigma_{\text{ID}}$  and between SFR and  $\sigma_{\text{ID}}$ , the signs of which can depend on the simulation and details of the cross-correlation measurement, indicate that the variations in velocity dispersion temporally coincide with variations in SFR and  $\dot{M}_{\text{gas}}$ , but the causality (i.e. whether accretion or/and stellar feedback drives enhancements in  $\sigma_{\text{ID}}$ ) cannot be determined from this analysis.

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## REFERENCES

- Agertz O., Lake G., Teyssier R., Moore B., Mayer L., Romeo A. B., 2009, *MNRAS*, 392, 294

- Anglés-Alcázar D., Faucher-Giguère C.-A., Kereš D., Hopkins P. F., Quataert E., Murray N., 2017, *MNRAS*, 470, 4698
- Bellocchi E., Arribas S., Colina L., Miralles-Caballero D., 2013, *A&A*, 557, A59
- Bellocchi E., Arribas S., Colina L., 2016, *A&A*, 591, A85
- Bouché N., Murphy M. T., Kacprzak G. G., Péroux C., Contini T., Martin C. L., Dessauges-Zavadsky M., 2013, *Science*, 341, 50
- Bournaud F. et al., 2011, *ApJ*, 730, 4
- Brinckmann J., Charlot S., White S. D. M., Tremonti C., Kauffmann G., Heckman T., Brinkmann J., 2004, *MNRAS*, 351, 1151
- Ceverino D., Dekel A., Bournaud F., 2010, *MNRAS*, 404, 2151
- Cresci G. et al., 2009, *ApJ*, 697, 115
- de Zeeuw P. T. et al., 2002, *MNRAS*, 329, 513
- Dekel A., Sari R., Ceverino D., 2009, *ApJ*, 703, 785
- Di Teodoro E. M., Fraternali F., 2015, *MNRAS*, 451, 3021
- Di Teodoro E. M., Fraternali F., Miller S. H., 2016, *A&A*, 594, A77
- Dib S., Bell E., Burkert A., 2006, *ApJ*, 638, 797
- El-Badry K., Wetzel A., Geha M., Hopkins P. F., Kereš D., Chan T. K., Faucher-Giguère C.-A., 2016, *ApJ*, 820, 131
- El-Badry K., Wetzel A. R., Geha M., Quataert E., Hopkins P. F., Kereš D., Chan T. K., Faucher-Giguère C.-A., 2017, *ApJ*, 835, 193
- Elmegreen B. G., Burkert A., 2010, *ApJ*, 712, 294
- Epinat B. et al., 2008, *MNRAS*, 388, 500
- Epinat B., Amram P., Balkowski C., Marcelin M., 2010, *MNRAS*, 401, 2113
- Epinat B. et al., 2012, *A&A*, 539, A92
- Falcón-Barroso J. et al., 2017, *A&A*, 597, A48
- Faucher-Giguère C.-A., 2018, *MNRAS*, 473, 3717
- Faucher-Giguère C.-A., Lidz A., Zaldarriaga M., Hernquist L., 2009, *ApJ*, 703, 1416
- Faucher-Giguère C.-A., Kereš D., Ma C.-P., 2011, *MNRAS*, 417, 2982
- Faucher-Giguère C.-A., Quataert E., Hopkins P. F., 2013, *MNRAS*, 433, 1970
- Faucher-Giguère C.-A., Hopkins P. F., Kereš D., Muratov A. L., Quataert E., Murray N., 2015, *MNRAS*, 449, 987
- Ferland G. J., Korista K. T., Verner D. A., Ferguson J. W., Kingdon J. B., Verner E. M., 1998, *PASP*, 110, 761
- Flores H., Hammer F., Puech M., Amram P., Balkowski C., 2006, *A&A*, 455, 107
- Förster Schreiber N. M. et al., 2009, *ApJ*, 706, 1364
- Furlong M. et al., 2015, *MNRAS*, 450, 4486
- Genel S., Dekel A., Cacciato M., 2012, *MNRAS*, 425, 788
- Genzel R. et al., 2011, *ApJ*, 733, 101
- Glazebrook K., 2013, *PASA*, 30, 56
- Gnerucci A. et al., 2011, *A&A*, 528, A88
- Gonçalves T. S. et al., 2010, *ApJ*, 724, 1373
- Green A. W. et al., 2010, *Nature*, 467, 684
- Green A. W. et al., 2014, *MNRAS*, 437, 1070
- Grudić M. Y., Hopkins P. F., Faucher-Giguère C.-A., Quataert E., Murray N., Kereš D., 2018, *MNRAS*, 475, 3511
- Harrison C. M. et al., 2017, *MNRAS*, 467, 1965
- Hayward C. C., Hopkins P. F., 2017, *MNRAS*, 465, 1682
- Hayward C. C., Torrey P., Springel V., Hernquist L., Vogelsberger M., 2014a, *MNRAS*, 442, 1992
- Hayward C. C. et al., 2014b, *MNRAS*, 445, 1598
- Helfer T. T., Thornley M. D., Regan M. W., Wong T., Sheth K., Vogel S. N., Blitz L., Bock D. C.-J., 2003, *ApJS*, 145, 259
- Hodge J. A., Carilli C. L., Walter F., de Blok W. J. G., Riechers D., Daddi E., Lentati L., 2012, *ApJ*, 760, 11
- Hopkins P. F., 2013, *MNRAS*, 428, 2840
- Hopkins P. F., 2015, *MNRAS*, 450, 53
- Hopkins P. F., Kereš D., Murray N., 2013a, *MNRAS*, 432, 2639
- Hopkins P. F., Narayanan D., Murray N., 2013b, *MNRAS*, 432, 2647
- Hopkins P. F., Kereš D., Oñorbe J., Faucher-Giguère C.-A., Quataert E., Murray N., Bullock J. S., 2014, *MNRAS*, 445, 581
- Hopkins P. F. et al., 2017, *MNRAS*, 480, 800
- Hopkins P. F. et al., 2018, *MNRAS*, 477, 1578
- Hung C.-L. et al., 2015, *ApJ*, 803, 62
- Hung C.-L., Hayward C. C., Smith H. A., Ashby M. L. N., Lanz L., Martínez-Galarza J. R., Sanders D. B., Zezas A., 2016, *ApJ*, 816, 99
- Ianjamasimanana R., de Blok W. J. G., Walter F., Heald G. H., 2012, *AJ*, 144, 96
- Johnson H. L. et al., 2017, *MNRAS*, 474, 5076
- Jones T. A., Swinbank A. M., Ellis R. S., Richard J., Stark D. P., 2010, *MNRAS*, 404, 1247
- Kam Z. S., Carignan C., Chemin L., Amram P., Epinat B., 2015, *MNRAS*, 449, 4048
- Kassin S. A. et al., 2012, *ApJ*, 758, 106
- Kassin S. A., Brooks A., Governato F., Weiner B. J., Gardner J. P., 2014, *ApJ*, 790, 89
- Kauffmann G. et al., 2003, *MNRAS*, 341, 33
- Kennicutt R. C., Jr, 1998, *ARA&A*, 36, 189
- Kereš D., Hernquist L., 2009, *ApJ*, 700, L1
- Kim J.-h. et al., 2014, *ApJS*, 210, 14
- Knollmann S. R., Knebe A., 2009, *ApJS*, 182, 608
- Kroupa P., 2001, *MNRAS*, 322, 231
- Krumholz M., Burkert A., 2010, *ApJ*, 724, 895
- Krumholz M. R., Burkert B., 2016, *MNRAS*, 458, 1671
- Krumholz M. R., Gnedin N. Y., 2011, *ApJ*, 729, 36
- Krumholz M. R., Burkert B., Forbes J. C., Crocker R. M., 2018, *MNRAS*, 477, 2716
- Law D. R., Steidel C. C., Erb D. K., Larkin J. E., Pettini M., Shapley A. E., Wright S. A., 2009, *ApJ*, 697, 2057
- Leethochawalit N., Jones T. A., Ellis R. S., Stark D. P., Richard J., Zitrin A., Auger M., 2016, *ApJ*, 820, 84
- Lehnert M. D., Nesvadba N. P. H., Le Tiran L., Di Matteo P., van Driel W., Douglas L. S., Chemin L., Bournaud F., 2009, *ApJ*, 699, 1660
- Lehnert M. D., Le Tiran L., Nesvadba N. P. H., van Driel W., Boulanger F., Di Matteo P., 2013, *A&A*, 555, A72
- Leitherer C. et al., 1999, *ApJS*, 123, 3
- Lemoine-Busserolle M., Bunker A., Lamareille F., Kissler-Patig M., 2010, *MNRAS*, 401, 1657
- Livermore R. C. et al., 2015, *MNRAS*, 450, 1812
- Martizzi D., Faucher-Giguère C.-A., Quataert E., 2015, *MNRAS*, 450, 504
- Mason C. A. et al., 2017, *ApJ*, 838, 14
- Mieda E., Wright S. A., Larkin J. E., Armus L., Juneau S., Salim S., Murray N., 2016, *ApJ*, 831, 78
- Molina J., Ibar E., Swinbank A. M., Sobral D., Best P. N., Smail I., Escala A., Cirasuolo M., 2016, *MNRAS*, 466, 892
- Muratov A. L., Kereš D., Faucher-Giguère C.-A., Hopkins P. F., Quataert E., Murray N., 2015, *MNRAS*, 454, 2691
- Noeske K. G. et al., 2007, *ApJ*, 660, L43
- Oliva-Altamirano P., Fisher D. B., Glazebrook K., Wisnioski E., Bekiaris G., Bassett R., Obreschkow D., Abraham R., 2018, *MNRAS*, 474, 522
- Orr M. et al., 2017, *MNRAS*, 478, 3653
- Ostriker E. C., Shetty R., 2011, *ApJ*, 731, 41
- Pineda J. C. B., Hayward C. C., Springel V., Mendes de Oliveira C., 2017, *MNRAS*, 466, 63
- Price D. J., Monaghan J. J., 2007, *MNRAS*, 374, 1347
- Queyrel J. et al., 2012, *A&A*, 539, A93
- Rodrigues M., Hammer F., Flores H., Puech M., Athanassoula E., 2016, *MNRAS*, 465, 1157
- Salim S. et al., 2007, *ApJS*, 173, 267
- Schmidt M., 1959, *ApJ*, 129, 243
- Shetty R., Ostriker E. C., 2012, *ApJ*, 754, 2
- Simons R. C. et al., 2016, *ApJ*, 830, 14
- Sparre M. et al., 2015, *MNRAS*, 447, 3548
- Sparre M., Hayward C. C., Feldmann R., Faucher-Giguère C.-A., Muratov A. L., Kereš D., Hopkins P. F., 2017, *MNRAS*, 466, 88
- Speagle J. S., Steinhardt C. L., Capak P. L., Silverman J. D., 2014, *ApJS*, 214, 15
- Springel V., 2005, *MNRAS*, 364, 1105
- Springel V., 2010, *MNRAS*, 401, 791
- Stilp A. M., Dalcanton J. J., Skillman E., Warren S. R., Ott J., Koribalski B., 2013, *ApJ*, 773, 88
- Stott J. P. et al., 2016, *MNRAS*, 457, 1888



- Swinbank M. et al., 2017, *MNRAS*, 467, 3140
- Swinbank A. M., Sobral D., Smail I., Geach J. E., Best P. N., McCarthy I. G., Crain R. A., Theuns T., 2012a, *MNRAS*, 426, 935
- Swinbank A. M., Smail I., Sobral D., Theuns T., Best P. N., Geach J. E., 2012b, *ApJ*, 760, 130
- Tacconi L. J. et al., 2010, *Nature*, 463, 781
- Thompson T. A., Quataert E., Murray N., 2005, *ApJ*, 630, 167
- Torrey P., Hopkins P. F., Faucher-Giguère C.-A., Vogelsberger M., Quataert E., Kereš D., Murray N., 2017, *MNRAS*, 467, 2301
- Turner O. J. et al., 2017, *MNRAS*, 471, 1280
- Wada K., Meurer G., Norman C. A., 2002, *ApJ*, 577, 197
- Walter F., Brinks E., de Blok W. J. G., Bigiel F., Kennicutt R. C., Jr, Thornley M. D., Leroy A., 2008, *AJ*, 136, 2563
- Wisnioski E. et al., 2011, *MNRAS*, 417, 2601
- Wisnioski E. et al., 2015, *ApJ*, 799, 209
- Yuan T. et al., 2017, *ApJ*, 850, 61
- Zhou L. et al., 2017, *MNRAS*, 470, 4573

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